Tire/road contact modeling for the in-vehicle noise prediction

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ABSTRACT

A numerical model for the contact between a wheel-air-tire system and a road surface is presented. The forces calculated at the center of wheel are to be used in a full numerical model of a vehicle for the in-vehicle noise prediction. The tire/road contact modeling is a difficult task because of the complex structure of the tire and the roughness of the road surface. Two numerical approaches are compared to each other in the present study: the first one solves directly the dynamic equation and the second one uses the static contact force to calculate the vibration of the tire. The numerical results of the forces at the wheel center have been compared to those of measurements conducted by PSA Peugeot Citroën. The comparison shows good agreement in the low frequency range up to 230Hz.

Keywords: Tire/road contact, in-vehicle noise   I-INCE Classification of Subjects Number(s): 11.7.1

1. INTRODUCTION

The tire/road contact is one of the main sources of the in-vehicle noise for passenger cars in the low frequency range (1). However the experiments on tire/road contact are expensive and a full dynamic numerical modeling is time consuming. Recently a multi-asperity approach has been developped (2, 3) and the contact pressure calculated by this approach is strongly correlated with the rolling noise (4, 5). In the present study, two numerical approaches are compared to each other: the first one solves directly the dynamic equation and the second one uses the static contact force to calculate the vibration of the tire. The numerical results of the forces at the wheel center will then be compared to those of measurements conducted by PSA Peugeot Citroën before concluding remarks.

2. NUMERICAL MODELING OF THE TIRE/ROAD CONTACT

2.1 Displacement superposition

For a wheel rolling on a smooth road, we suppose that the motion of the wheel and tire is governed by the following equation

$$\mathbf{g}(\mathbf{u_s}) = \mathbf{F}_s \tag{1}$$

where $\mathbf{u_s}$ the displacement vector, $\mathbf{F}_s$ the contact force between the tire and the smooth road, $\mathbf{g}$ is a function which links them.

The problem of rolling contact between a smooth tire and a smooth road can be solved by using Abaqus. Figure 1 shows an example of the force calculated at the wheel center.

In order to study the contact between the tire and a rough road, one can add a small oscillation $\mathbf{u}$ to $\mathbf{u_s}$, then equation (1) becomes:

$$\mathbf{g}(\mathbf{u_s} + \mathbf{u}) = \mathbf{F}_c \tag{2}$$

where $\mathbf{F}_c$ is the contact pressure between the tire and a rough road surface. The last equation can be linearized in the following way :

$$\mathbf{g}(\mathbf{u_s}) + \frac{\partial \mathbf{g}}{\partial \mathbf{u}}(\mathbf{u_s})\mathbf{u} = \mathbf{F}_c \tag{3}$$

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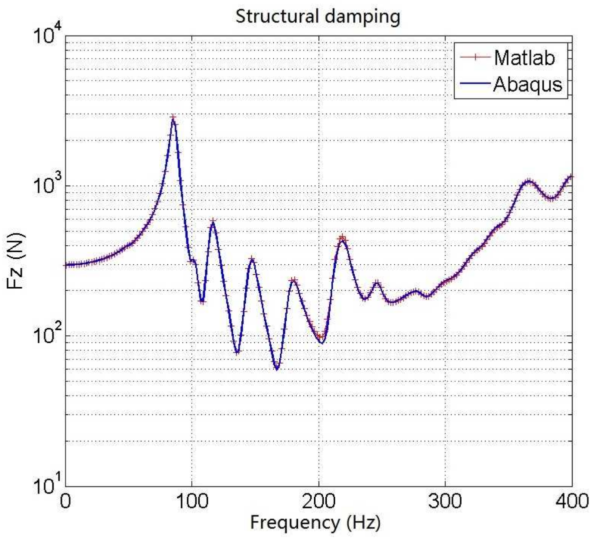

Figure 1 – Vertical force calculated at the wheel center.

The tangent stiffness matrix is defined by the following equation:

$$\frac{\partial \mathbf{g}}{\partial \mathbf{u}}(\mathbf{u_s}) = \mathbf{K} \tag{4}$$

From the last four equations one deduces

$$\mathbf{K}\,\mathbf{u} = \mathbf{F}_c - \mathbf{F}_s \tag{5}$$

2.2 Full dynamic model

By adding the mass and damping terms, the dynamic motion equation of a wheel-air-tire system can be obtained,

$$\mathbf{M}\,\ddot{\mathbf{u}} + \mathbf{C}\,\dot{\mathbf{u}} + \mathbf{K}\,\mathbf{u} = \mathbf{F}_c - \mathbf{F}_s \tag{6}$$

where the matrices $\mathbf{M}$, $\mathbf{K}$ and $\mathbf{C}$ are the mass matrix, stiffness matrix and damping matrix respectively. Their components are extracted from Abaqus. The following contact conditions are to be satisfied in the tire/road contact zone,

$$u_{Xi} = 0, \quad u_{Yi} = 0, \quad u_{Zi} = f_{road}(X_i, Y_i) - Z_i(X_i, Y_i) \quad \text{and} \quad F_c^v > 0 \tag{7}$$

where X_i, Y_i represent the longitudinal and lateral positions in the moving reference of the car. In the contact zone, the tangential displacement is neglected ($u_{Xi} = u_{Yi} = 0$). The function $f_{road}(X_i, Y_i)$ and $Z_i(X_i, Y_i)$ represent the road surface and the tire height respectively. The normal displacement continuity is satisfied and compress normal force F_c^v is supposed to be positive.

By using Newmark method, one solves the following equation instead of equation (1),

$$\mathbf{K}_d\,\mathbf{u} = \mathbf{F}_h + \mathbf{F}_c - \mathbf{F}_s \tag{8}$$

where $\mathbf{K}_d$ is the dynamic stiffness matrix defined by Newmark method and $\mathbf{F}_h$ the historic force.

The last equation has been solved by using Matlab for a tire rolling on a cleat as shown in figure 2. The longitudinal and normal forces at the wheel center have been calculated and their spectrums are shown in figure 3 by the blue curve. The red and black curves show the measurements on two different tires. The numerical results agree qualitatively well with the experimental results. However the computation lasted more than one day which is too long for industrial applications.

2.3 Two-step static-dynamic model

The contact force in static conditions can be calculated by solving the following equation.

$$\mathbf{K}\,\mathbf{u} = \mathbf{F}_c - \mathbf{F}_s \tag{9}$$

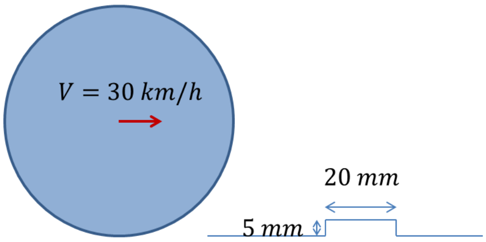

Figure 2 – Tire rolling on a cleat.

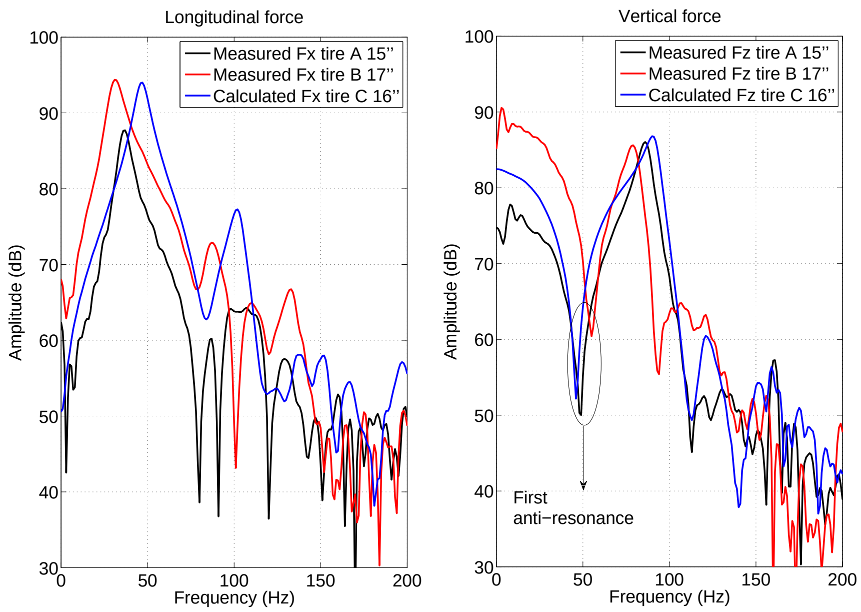

Figure 3 – Spectrums of the longitudinal (left) and vertical (right) forces, red and black curves showing the measured results for two different tires, the blue one showing the numerical results.

For low frequencies, the static and dynamic contact forces are supposed to be close to each other. At constant speed V, the longitudinal position is $X(t) = Vt$, then the static contact pressure and the displacement are transformed into time functions

$$\mathbf{F}_c(Vt, Y(t)) = \mathbf{f}_c(t), \quad \mathbf{U}_c(Vt, Y(t)) = \mathbf{u}_c(t) \tag{10}$$

The spectrums of the displacement $\mathbf{u}_c$ and the force $\mathbf{f}_c$ at one point are shown in Figures 4 and 5.

The dynamic response of the tire to the excitations calculated in static conditions is the solution of the following equation :

$$\begin{cases} \mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{f}_c(t) \\ \mathbf{u}^{imp} = \mathbf{u}_c(t) \end{cases} \tag{11}$$

This equation has been solved by using the method of Lagrange multipliers for frequencies from 0 to 400Hz with a frequency resolution of one Hertz. The calculation lasted 4000 secondes (1.1 hours) which is to be compared to 30 hours for the full dynamic calculation. The spectrums of the longitudinal and vertical forces calculated at the wheel center by using the two methods are compared in figure 6. The red and black curves show the results of the full dynamic method and two step static-dynamic method respectively. The curves are close to each other in the frequency range from 0 to 230 Hz.

3. CONCLUSIONS

A numerical model for the contact between a wheel-air-tire system and a road is presented. The forces calculated at the center of wheel would be used in a full numerical model of a vehicle for the in-vehicle noise prediction. Two numerical approaches are compared to each other in the present study: the first one solves

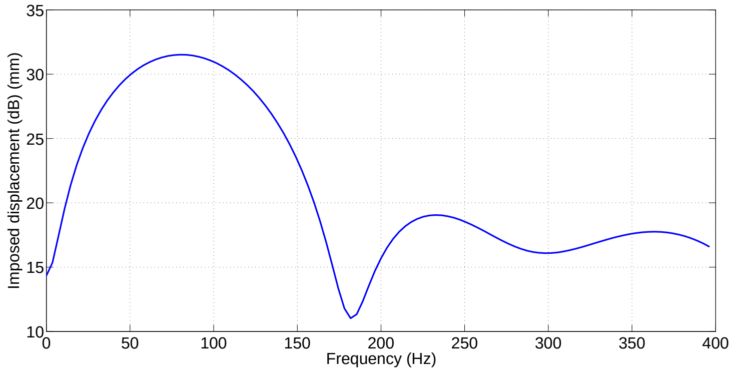

Figure 4 – Spectrum of the displacement imposed at one point.

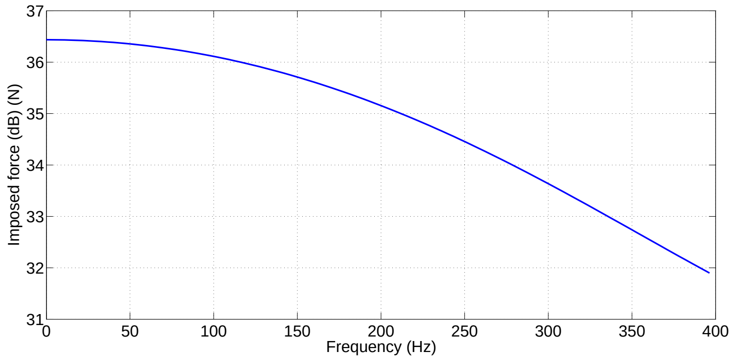

Figure 5 – Spectrum of the force imposed at one point.

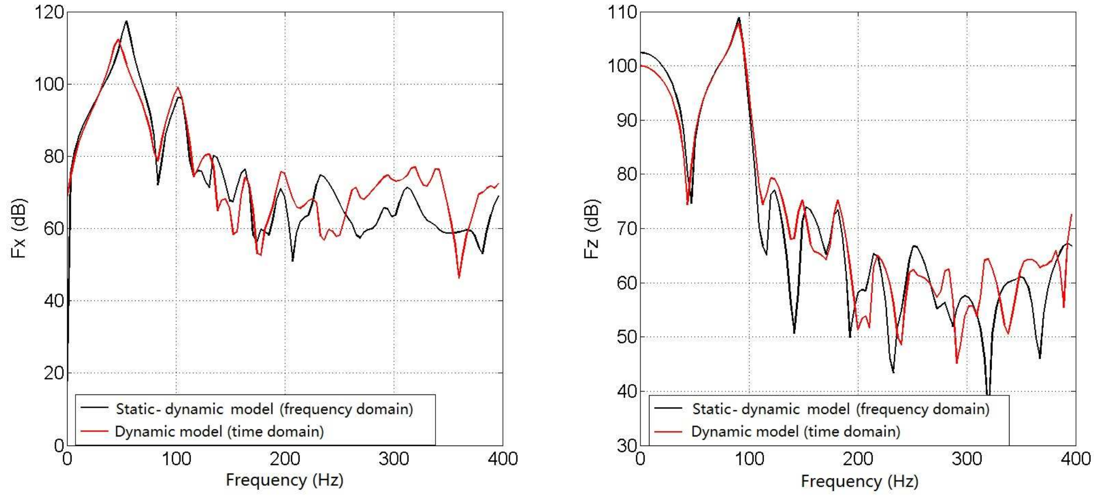

Figure 6 – Longitudinal (left) and vertical (right) forces calculated at the wheel center by using the full dynamic model (red curves) and two step static-dynamic model (black curves).

directly the dynamic equation and the second one uses the static contact force to calculate the vibration of the tire. The two models are applied to the problem of a tire rolling on a cleat and they give similar results of the forces at the wheel center but the two step static-dynamic model is much less time consuming. Finally the numerical results have been compared with those of measurements conducted by PSA Peugeot Citroën. The comparison shows good agreement in the low frequency range up to 230Hz. The application to real rough road surfaces is in progress.

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